Production Research Report No. 35

MOISTURE AND TEMPERATURE INFLUENCES ON SPRING WHEAT PRODUCTION

In the Plains Area of Montana

By T. J. ARMY and W. D. HANSON

Agricultural Research Service
UNITED STATES DEPARTMENT OF AGRICULTURE
In Cooperation With the
MONTANA AGRICULTURAL EXPERIMENT STATION

531710—60

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Washington, D.C. Issued July 1960

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C. - Price 15 cents

Moisture and Temperature Influences on Spring Wheat Production

In the Plains Area of Montana[1]

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The Great Plains area of Montana is characterized by wide climatic extremes. Variability in precipitation, temperature, wind velocity, and other associated climatic factors is reflected by large yearly fluctuations in agricultural production. Under dryland farming practices, crop losses are frequently extensive and severe as a result of unfavorable weather phenomena.

The need for obtaining a comprehensive understanding of weather conditions during the crop-growing season in the northern Great Plains was recognized early after the virgin sod was broken for crop production. Interest in the subject of semiarid agriculture versus weather has continued to this day.

Two main lines of study have generally been followed by investigators of climate-crop relationships. Analyses of meteorological cycles have received considerable attention. Sanderson (*15, p. 3*)[4] remarked that such cycles "exercised a particular attraction on economists owing to the possibility they seemed to offer of an explanation of economic cycles by meteorological and cosmic events." Because meteorological data for United States areas have, in general, been recorded only since the beginning of the 20th century, those now available are inadequate for identifying any definite climatic cycles. Existence of a 9-year cycle for wheat yields in Montana was suggested in 1942 by Bean (*1*). Subsequent weather records in Montana have failed to reveal any such cycle.

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[1] Joint contribution of the U.S. Department of Agriculture and the Montana Agricultural Experiment Station, cooperating.

[2] The authors wish to acknowledge the capable technical assistance received from former and present personnel of the North Montana and Huntley Branch Stations of the Montana Agricultural Experiment Station, at which the data used in the study reported here were collected. Consultation and assistance of J. C. Hide, Bernard Ostel, and Hobart Cross in the early phases of the study are greatly appreciated. Without the interest and efforts of R. L. Smith and B. L. Lisenbe, of the Statistical Laboratory of the Texas Agricultural Experiment Station, the study could not have been made.

[3] At the time of the preparation of this report, biometrician, Biometrical Services, Agricultural Research Service.

[4] Italic numbers in parentheses refer to Literature Cited, p. 25.

The second approach used in crop-climate studies has centered on the use of simple and multiple correlation and regression techniques. Investigators hoped that through the development of regression formulas a yield forecast could be made early in the growing season of the crop. Efforts to extrapolate regression formulas have frequently failed, however, and much skepticism has been expressed regarding the usefulness of such formulas in crop forecasting. However, if used properly, multiple regression analyses should serve a useful purpose in predicting crop yields. In addition, such statistical analyses should aid in evaluating the magnitude of the effects of various climatic variables during specific phenologic periods in the development of the crop on final grain yields.

The study reported here was an effort to contribute through correlation and multiple regression analyses to the understanding of effects of soil moisture supply at seeding, precipitation, and temperature on spring wheat production in the northern Great Plains.

Literature Review

Blair (*2*) early reported on the significance of growing-season rainfall to yield of spring wheat in the northern Great Plains. He had found that grain yield in the Dakotas was significantly correlated with May and June rainfall, and had found evidence that it was affected by temperature. In North Dakota the limited data suggested that "good yields in dry years were accompanied by cool weather in May, and poor yields in normally wet years by very warm weather" (*2*). In later articles Blair (*3, 4*) concluded that the mean temperature in June was about of equal importance in determining yield of wheat as was rainfall in May and June, and "that a considerable part of the apparent effect of either precipitation or temperature upon [spring wheat] yield is really due to the accompanying effect of the other" (*4*).

Connor (*8*), in Manitoba, examined in detail spring wheat yield and weather for individual 30-day periods from the date of seeding to harvest. In each of the four 30-day periods following seeding and in all combinations of them, an increase in precipitation brought increased yield. Precipitation effects were small, however, when the fourth period was considered independently. Rainfall during the third 30-day period after sowing had the greatest beneficial effect on yield. The correlation coefficient between grain yield and precipitation during the complete growing season (four 30-day periods) was larger than that for any individual period. This suggested to Connor that the effect of precipitation on grain yield was cumulative. Large diurnal changes in temperature during the third 30-day period after seeding reduced yield considerably. Diurnal temperature variations in the other 30-day periods had little influence on grain yield. Minimum temperatures were negatively correlated with yield in the third period (after heading) and had no measurable effect in any of the other periods. Connor concluded that "the wheat plant demands moisture and coolness prior to the 91st day after sowing, and the subsequent yield is most reduced by large ranges of temperature during the third 30 days after sowing." Patton (*13*), in evaluating weather and spring wheat yield relationships in Montana, found that high temperatures around heading time were particularly detrimental to wheat yields. According to his findings, hot winds in

June and July were more important in determining final grain yield than was precipitation from April to August.

Chilcott (*5*) early concluded that seasonal precipitation was not the dominant factor limiting crop yields in the Great Plains. He considered that hot winds, diseases, and insects were of equal importance to precipitation even in the semiarid plains. In view of Hopkins' (*11*) detailed study of climate and spring wheat yields in Saskatchewan and Alberta, it appears that Chilcott underestimated the importance of precipitation. Hopkins used the statistical procedure, "regression integral," developed by Fisher (*10*) to study the effect of rainfall and temperatures at different periods in the growth cycle on the yield of grain. Hopkins found that spring wheat yields were influenced less by temperature than by rainfall during the growing season. Furthermore, the results of Hopkins' study indicated that "the influence of weather on wheat yields is not largely exerted in a few relatively short periods of time, but extends at least throughout the growing season." The cumulative effect of rainfall and temperature is again implied. Although Hopkins did not consider soil moisture conditions, he did indicate that soil moisture at seeding could be expected to influence the relationship of yield and weather during particular growth periods. Cole and Mathews (*7*) had previously shown that a correlation of 0.76 existed between the total quantity of water removed from the soil and the yield of grain from a spring wheat crop. According to Cole and Mathews, the supply of soil moisture at seeding was seldom adequate to carry the crop to maturity. The usual growing season in the Spring Wheat Belt generally involved an interaction between soil moisture supplies at seeding and growing season climate.

Pengra (*14*) recently concluded that in the Great Plains seasonal precipitation is rarely sufficient to overcome a marked moisture deficiency at seeding time. Consequently, according to Pengra, preseasonal precipitation (or soil moisture supply at seeding time) appears to be at least as significant in the production of small grains as is precipitation received during the growing season.

Davis and Pallesen (*9*) also used the regression procedure developed by Fisher (*10*) and simplified later by Houseman (*12*). They found that with spring wheat in North Dakota the greatest beneficial effect from rain during the growing season occurs about 3 weeks before the average heading date. However, additional rainfall at any time during the growing season caused an increase in yield. These investigators did not include soil moisture or temperature effects in evaluating precipitation-yield relationships.

In most of the studies referred to in the preceding discussion, data were extremely limited. Results of studies cited showed clearly, however, that moisture and temperature are major determinants of spring wheat yield in the northern Great Plains, and that soil moisture supply at seeding and growing-season weather interact as factors affecting yield. They indicated that equal increments of rainfall or of heat occurring at different times during the growing season exert dissimilar influences upon yield.

Futhermore, although it is well known that soil moisture, rainfall, and temperatures affect spring wheat yields, there is apparently no reported analysis wherein the effects of these three environmental factors on yields have been considered simultaneously. None of the studies with spring wheat cited here have produced regression equations that could satisfactorily be used for crop-prediction purposes.

Experimental Sites and Procedure

As one part of a dryland-farming research program (*5*), spring wheat was grown continuously and also was alternated with fallow at the Huntley and North Montana (Havre) Branch Stations of the Montana Agricultural Experiment Station from 1913 and 1917, respectively, to 1951. Because of incompleteness of records of soil moisture for some years, the study reported here was based only on data for periods terminating in 1946 at Huntley and 1947 at Havre. Data were taken from the experimental rotation series designated as MC in annual reports and field notebooks. Continuous-cropping data were obtained from rotation MC–A plots, spring plowed 4 to 6 inches deep, and for wheat following fallow from records of the MC–C and MC–D plots.

The soils at Havre and Huntley are deep clay loam members of the Brown Great Soil Group. Those at Havre were derived from glacial till and are of the Joplin series. The soil at Huntley is alluvial in origin and is tentatively classified as of the Nunn and Fly Creek series. No fertilizer was applied to any of the plots within the period of experimentation.

Plots were 0.1 acre in size and unreplicated. Two adjacent plots were alternately cropped and fallowed.

Crop varieties grown and average dates of seeding, heading, and harvest are shown in table 1.

Complete weather records as prescribed by the U.S. Weather Bureau were maintained at each station during the entire period of experimentation.

Soil samples for moisture determinations at Havre and Huntley were taken at 1-foot intervals to a depth of 4 feet shortly after seeding and at other stages in the growth of the spring wheat crop. On the basis of previously determined volume weights [5,6] of the soils at each of these locations, moisture percentages were converted to inches of water in the 4-foot profile.

TABLE 1.—*Spring wheat varieties used in study and average dates of seeding, heading, and harvest on experimental plots*

Station	Varieties used, and years of use	Average date [1] of— Seeding	Heading	Harvest
Havre	Kubanka, 1917; Peliss, 1918–28; Marquis, 1929–45; Rescue, 1946–47	April 25 (5)	June 29 (6)	August 2 (7).
Huntley	Kubanka, 1913–41; Ceres, 1942–46	April 18 (13)	June 26 (10)	July 27 (9).

[1] Numbers in parentheses are standard deviations in days.

[5] AASHEIM, T. S. INTERRELATIONSHIPS OF PRECIPITATION, SOIL MOISTURE, AND SPRING WHEAT PRODUCTION IN NORTHERN MONTANA. 1954. [Unpublished master's thesis. Copy on file Montana State College.]

[6] SEAMANS, A. E. SOIL MOISTURE RECORDS AT THE HUNTLEY BRANCH STATION 1912 TO 1946. 1949. [Unpublished.]

Grain Yields

Long-term averages of spring wheat yields on plots continuously cropped and on plots alternately cropped and fallowed at Havre and Huntley are shown in table 2. The tabulated yield values, in pounds of grain per 0.1 acre, are averages of the actual plot yields and are those used in the regression analyses.

At Havre the wheat yield on plots that were alternately cropped and fallowed averaged about twice as great as that obtained by continuous cropping. At Huntley the wheat yield on alternately cropped plots averaged about 1⅔ times as great as that on continuously cropped plots.

Under semiarid conditions the mean yield may not indicate dependably the value of a particular cropping practice, since the individual yearly yields are not normally distributed. Answering the question whether the crop-fallow system is superior to the continuous-cropping system at any given location involves analyses of the distribution of yields and of relative costs for each cropping system. A cost analysis was not included in the study reported here. However, information obtainable from the yield distributions would be helpful in evaluating the cropping systems. The individual spring wheat yields obtained on plots continuously cropped and on plots alternately cropped and fallowed at Havre and Huntley are shown in order of magnitude in table 3.

The yields would not be expected to exhibit any basic type of distribution. A transformation of the data was necessary to reduce the distribution to a form easily calculated and readily usable. When trace yields—yields of less than 1.0 bushel per acre—were eliminated, the remaining yield values were found to fit approximately a modified log-normal distribution.

The probability of obtaining a trace yield and that of obtaining more than a trace yield were estimated for each station and cropping system. The results are presented in table 4.

The nontrace yields were plotted on log-probability paper as exemplified in figure 1. The variable t is the standardized t associated with the cumulative probability $\frac{r}{n+1}$, where r is the rank of an entry and n is the total number of entries (*6*). The second variable for plotting was $Y=\log(X+A)$, where X is an annual yield greater than a trace and A is the constant that gives an approximate linear plot for t and Y. (For each location and cropping sequence, the values of Y and t for several selected values of A were plotted to determine which of these values of A gave an approximate linear plot.) The cumulative plots for the four sets of data were resolved into linear approximations.

TABLE 2.—*Average spring wheat yields on plots continuously cropped and on plots alternately cropped and fallowed*

Station and period	Plots continuously cropped (MC–A series)		Plots alternately cropped (MC–C and MC–D series)	
	Lb./0.1 acre	*Bu./acre*	*Lb./0.1 acre*	*Bu./acre*
Havre, 1917–47	47. 00	7. 8	94. 74	15. 8
Huntley, 1913–46	49. 76	8. 3	83. 38	13. 9

Table 3.—*Ordered spring wheat yields on plots continuously cropped and on plots alternately cropped and fallowed*

Order of magnitude	Yield per acre			
	Havre		Huntley	
	Continuous cropping	Alternate cropping	Continuous cropping	Alternate cropping
	Bushels	*Bushels*	*Bushels*	*Bushels*
1	0	0. 3	0	0
2	. 2	. 5	0	0
3	. 8	2. 2	0	. 2
4	. 8	3. 0	0	. 5
5	1. 2	5. 0	0	. 7
6	1. 5	5. 8	0	1. 5
7	1. 7	9. 0	0	2. 5
8	2. 2	9. 8	1. 2	2. 5
9	2. 8	10. 5	1. 5	2. 7
10	3. 0	10. 8	2. 0	4. 5
11	3. 5	11. 3	2. 3	5. 5
12	4. 0	11. 7	2. 8	6. 8
13	4. 2	12. 2	3. 0	9. 7
14	4. 3	12. 8	3. 8	10. 0
15	5. 2	13. 2	4. 3	10. 3
16	5. 7	13. 5	5. 0	10. 8
17	6. 2	13. 7	5. 5	11. 3
18	6. 3	15. 7	5. 8	12. 3
19	7. 2	16. 7	5. 8	13. 5
20	7. 2	18. 5	6. 3	17. 7
21	8. 4	19. 0	7. 0	18. 3
22	9. 7	19. 0	7. 5	18. 8
23	11. 8	19. 3	7. 8	19. 3
24	13. 2	20. 0	8. 2	19. 5
25	16. 0	22. 7	9. 0	20. 3
26	16. 0	24. 2	9. 0	20. 3
27	16. 3	27. 2	16. 0	20. 5
28	16. 7	31. 2	18. 3	21. 8
29	19. 2	31. 3	20. 7	22. 7
30	21. 7	37. 7	23. 5	23. 3
31	26. 2	41. 3	24. 2	28. 8
32			24. 5	31. 7
33			26. 7	36. 5
34			30. 3	47. 5

Table 4.—*Estimated probabilities of obtaining a trace yield and a non-trace yield, respectively, through continuous cropping and alternate cropping*

Station and cropping system	Probability of obtaining a trace yield ($X<1.0$ bu./acre)	Probability of obtaining a non-trace yield ($X \geq 1.0$ bu./acre)
Havre:		
Continuous cropping	0. 129	0. 871
Alternate cropping	. 065	. 935
Huntley:		
Continuous cropping	. 206	. 794
Alternate cropping	. 147	. 853

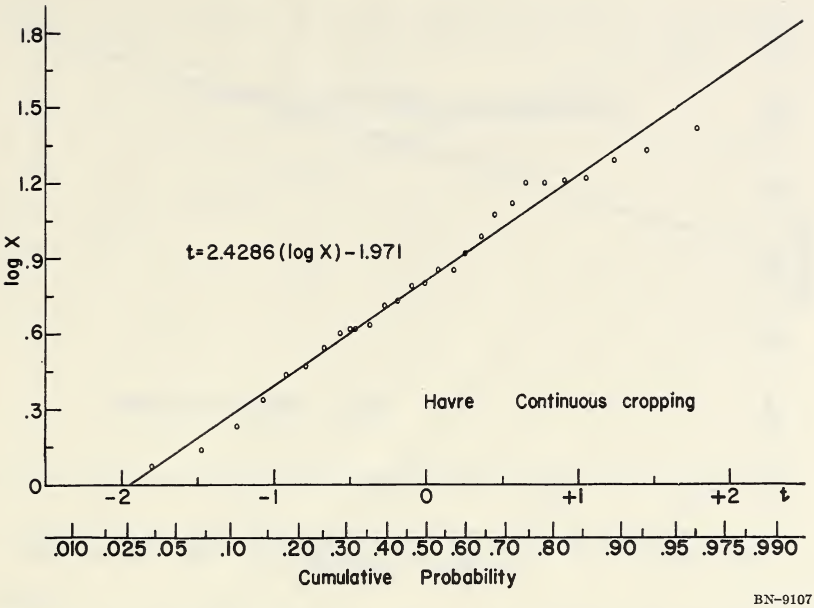

FIGURE 1.—Cumulative frequency of spring wheat yields amounting to 1.0 bushel or more per acre obtained by continuous cropping at Havre (X=yield in bushels per acre; n=27).

The regression relation for the scale conversion between t and Y[7] is obtained by use of the equation

$$t = b \log (X+A) - C$$

$$\text{where } b = \frac{\text{standard deviation of } t}{\text{standard deviation of } \log (X-A)}$$

$$\text{and } C = b[\text{mean of } \log (X+A)]$$

The regressions are summarized in table 5 and have been plotted in figures 1 to 4.

The cumulative probability for any nontrace yield (X) can be obtained directly from figure 1, 2, 3, or 4. Alternatively, t can be calculated from the regression and the cumulative probability obtained from any table of cumulative normal frequency distributions (*15*). Formulas for determining the probability of failing to obtain a yield of at least X bushels are given in the last column of table 5.

In using the information in table 5 it must be assumed that the year effects are random and that the yields compose an adequate sample of possible yields for continuous or alternate cropping. These assumptions can be criticized, of course, since the weather patterns may not be typical and crop varieties and agronomic practices are subject to continual improvement.

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[7] For this analysis the functional regression of Y on t has no meaning. Owing to the approximate nature of A, the orthogonal mean-square regression represents a refinement that is unwarranted for the analysis. The selected regression minimizes the triangular areas delineated by the regression line and the coordinates of any observation (*17*).

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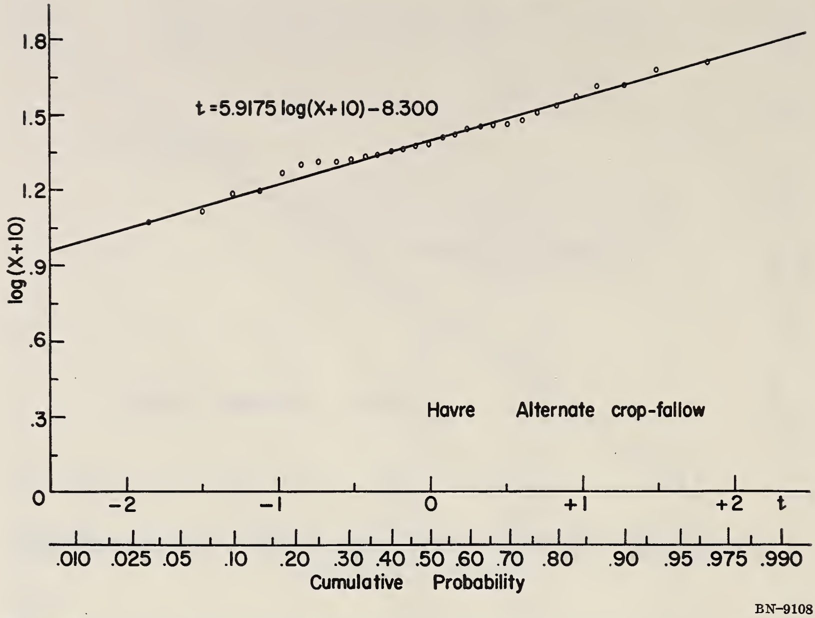

FIGURE 2.—Cumulative frequency of yields amounting to 1.0 bushel or more per acre obtained by alternate cropping at Havre (X=yield in bushels per acre; n =29).

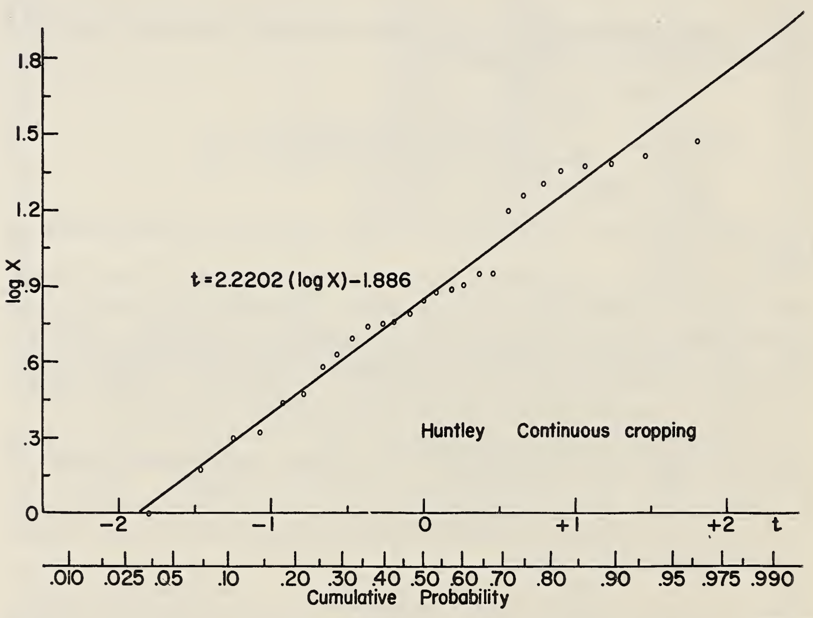

FIGURE 3.—Cumulative frequency of yields amounting to 1.0 bushel or more per acre obtained by continuous cropping at Huntley (X=yield in bushels per acre; n=27).

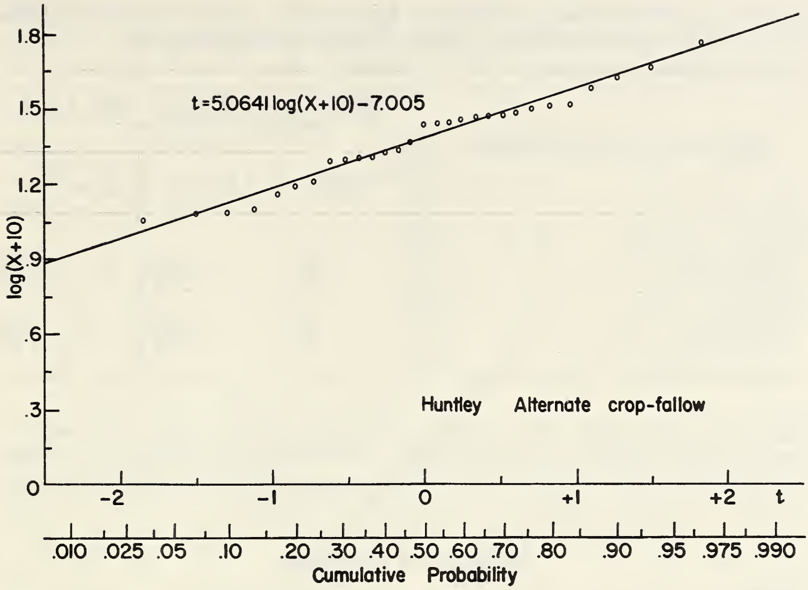

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FIGURE 4.—Cumulative frequency of yields amounting to 1.0 bushel or more per acre obtained by alternate cropping at Huntley (X=yield in bushels per acre; $n=29$).

Estimated probabilities of failure to obtain selected yield values are given in table 6. It can readily be seen in table 6 that the continuous-cropping practice is exceedingly hazardous at both Havre and Huntley. On the basis of existing data, yields under continuous cropping can be expected to amount to less than 5 bushels per acre in about 50 percent of the years at either location. On the other hand, yields on land fallowed in alternate years should amount to 5 bushels or more per acre in 85 percent of the years at Havre and in 73 percent of the years at Huntley. Even though wheat yields obtained on plots

TABLE 5.—*Formulas for computing the probability, in any year, of failing to obtain at least X bushels per acre*

Station and cropping system	Formula for t	Formula for determining probability of failing to obtain X yield
Havre:		
Continuous	$t=2.4286 \log X-1.971$	0.129+0.871 [Pr ($t\leq$calculated t)].
Alternate	$t=5.9175 \log (X+10)-8.300$	0.065+0.935 [Pr ($t\leq$calculated t)].
Huntley:		
Continuous	$t=2.2202 \log X-1.886$	0.206+0.794 [Pr ($t\leq$calculated t)].
Alternate	$t=5.0641 \log (X+10)-7.005$	0.147+0.853 [Pr ($t\leq$calculated t)].

Table 6.—*Estimated probabilities of failure to obtain selected yields through continuous cropping and alternate cropping*

Station and cropping system	Probability of failure to obtain a per-acre yield of at least—		
	5 bushels	8 bushels	12 bushels
Havre:			
Continuous	0. 47	0. 64	0. 78
Alternate	. 15	. 24	. 40
Huntley:			
Continuous	. 50	. 64	. 76
Alternate	. 27	. 37	. 50

fallowed in alternate years averaged less than twice those obtained by continuous cropping, over a long period the chance of obtaining at least a 12-bushel yield on fallowed land is greater than that of obtaining at least a 5-bushel yield by continuous cropping.

Method of Analysis

Studies employing simple correlation and multiple regression techniques were initiated to examine the interacting effects on spring wheat yield of (*a*) soil moisture supply at seeding and (*b*) precipitation and temperatures during the growing season.

Preliminary studies indicated that grain yield at either of the experimental locations was not correlated with daily minimum temperatures during the growing season. Daily mean temperatures usually have little value for study of responses of plants to temperature on the Great Plains, where large diurnal temperature fluctuations occur and hot days are often associated with cool nights. Accordingly, daily maximum temperatures in the growing season of spring wheat were used in the correlation and regression studies.

All pertinent crop and soil moisture data for each location were coded and punched into IBM cards. Daily weather records for each experimental site were supplied on IBM cards by Montana State College and the U.S. Weather Bureau. Within the years of cropping studied at each location, no yield values were omitted because they appeared to be erratic or unduly influenced by external disturbances not directly related to or measurable by soil moisture at seeding or growing-season precipitation and temperatures.

To determine the growth period in which the wheat plant was most responsive to a particular climatic factor, the growing season was divided into four periods. The periods selected were based on the major morphological and physiological changes occurring in the development of the wheat plant. The phenologic periods were: (1) seeding to tillering; (2) tillering to heading; (3) heading to soft dough; and (4) soft dough to harvest.

Examination of the cropping records for the study period indicated that dates of seeding, heading, and harvest were relatively constant. Standard deviations of seeding, heading, and harvest dates are shown in table 1. Dates of tillering and soft dough, which were not recorded in field notebooks, were estimated. In view of the limited variability

in the recorded dates of the major phenological periods, a constant set of growth-period dates was selected to conform with climatological weeks of the U.S. Weather Bureau. The phenologic periods referred to in this discussion, therefore, are averages for the period of experimentation. They are as follows:

	Havre	*Huntley*
Seeding to tillering:		
Week Nos.[1]	8–14	7–13.
Calendar dates	April 19–June 6	April 12–May 30.
Tillering to heading:		
Week Nos.[1]	15–17	14–16.
Calendar dates	June 7–June 27	May 31–June 20.
Heading to soft dough:		
Week Nos.[1]	18–21	17–20.
Calendar dates	June 28–July 25	June 21–July 18.
Soft dough to harvest:		
Week Nos.[1]	22–23	21–22.
Calendar dates	July 26–August 8	July 19–August 1.

[1] Climatological week numbers of the U.S. Weather Bureau.

The use of phenologic periods based upon climatological weeks greatly simplified the machine compilation of weather data for individual growth periods in each year of cropping. Weather data for each phenologic period were rapidly summarized by use of various IBM machines and weekly-weather-summary punch cards.

Simple correlation coefficients were calculated for grain yield and (1) soil moisture at seeding, (2) precipitation of each phenologic period, and (3) total daily maximum temperatures of each phenologic period. Multiple regression analyses were subsequently made with an IBM calculator according to procedures outlined by Snedecor (*16*).

Results

Mean values and standard deviations for soil moisture at seeding and for precipitation and maximum temperatures for each phenologic period are shown in table 7. Precipitation and temperature are both shown as totals, or the accumulated daily values, in each of the respective periods. It should be remembered, however, that in the regression equations presented later, both precipitation and maximum temperatures were used as total or summation values. In all of the subsequent statistical evaluations, grain yields are represented as pounds per 0.1 acre.

The results indicate great similarity between the two stations with regard to growing-season climate. On a daily basis the average precipitation a spring wheat crop receives is about the same at each of the locations, i.e., 0.058 inch at Havre and 0.056 inch at Huntley.

Maximum temperatures during the heading-to-harvest period were higher at Huntley than at Havre.

The simple correlation matrices (table 8) reveal that grain yields at Havre and Huntley were significantly correlated with the amount of soil moisture at seeding. Cropping sequence had little effect on the magnitude of the r value at either location. However, variation of soil moisture at seeding time, in itself, leaves unexplained a great part of the yearly variation of spring wheat yields at these Montana locations.

The relationship of yield to precipitation and maximum temperatures followed the same pattern at each location. Precipitation before heading was more highly correlated with yield than was heading-to-harvest precipitation in all but two instances. After heading,

TABLE 7.—*Means and standard deviations of soil moisture supply at seeding and of precipitation and total daily maximum temperatures for each phenologic period*

Station, environmental factor, and cropping system or phenologic period	Mean	Standard deviation
Havre:		
Soil moisture: [1]		
Continuous cropping.....inches..	6. 31	1. 18
Alternate cropping.....do....	8. 96	1. 17
Precipitation:		
Seeding to tillering.....do....	2. 57	1. 54
Tillering to heading.....do....	2. 07	1. 24
Heading to soft dough.....do....	1. 27	. 73
Soft dough to harvest.....do....	. 56	. 47
Maximum temperatures: [2]		
Seeding to tillering.....degrees F...	3, 231. 3 (65. 9)	194. 4
Tillering to heading.....do....	1, 580. 1 (75. 2)	120. 2
Heading to soft dough.....do....	2, 359. 9 (84. 3)	84. 4
Soft dough to harvest.....do....	1, 188. 9 (84. 9)	65. 0
Huntley:		
Soil moisture: [1]		
Continuous cropping.....inches..	7. 78	1. 59
Alternate cropping.....do....	8. 91	1. 74
Precipitation:		
Seeding to tillering.....do....	2. 55	1. 55
Tillering to heading.....do....	2. 04	1. 34
Heading to soft dough.....do....	1. 20	. 78
Soft dough to harvest.....do....	. 49	. 62
Maximum temperatures: [2]		
Seeding to tillering.....degrees F...	3, 265. 9 (66. 7)	220. 1
Tillering to heading.....do....	1, 585. 1 (75. 5)	108. 7
Heading to soft dough.....do....	2, 399. 6 (85. 7)	111. 1
Soft dough to harvest.....do....	1, 253. 3 (89. 5)	53. 8

[1] At Havre and Huntley, means of soil moisture available for plant growth are less by 4 to 4.5 inches than the means of total soil moisture tabulated here.
[2] Values given in parentheses are mean daily maximum temperatures.

temperatures were more highly correlated with grain yields than was precipitation in all cases. Precipitation effects on yields were positive and maximum temperature effects on yields were negative in all instances. These results agree with those previously reported (*3, 4, 8, 11*).

Precipitation during the seeding to tillering period appears to be more important under continuous cropping than under an alternate fallow system. Apparently the increased soil moisture reserves under fallow make the crop grown on fallowed land less dependent on early growing-season rainfall.

Because of the interrelationships of independent variables, simple correlation coefficients are often inadequate in establishing desired relationships between dependent and independent variables. It is readily apparent from table 8 that maximum temperatures were inversely and significantly correlated with precipitation in each respective growth period at each location. Soil moisture at seeding was significantly correlated with seeding-to-tillering precipitation at both stations. This correlation between soil moisture values and seeding-to-tillering precipitation may partially be explained by the inability of research workers to sample soils and seed the crop at the same time.

TABLE 8.—*Simple correlations of environmental factors with spring wheat yield and with each other*

Station, environmental factor, and phenologic period	Correlation [1] with—									
	Precipitation				Maximum temperatures				Grain yield	
	Seeding to tillering	Tillering to heading	Heading to soft dough	Soft dough to harvest	Seeding to tillering	Tillering to heading	Heading to soft dough	Soft dough to harvest	Continuous cropping	Alternate cropping
Havre:										
Soil moisture at seeding	+0.526	−0.146	+0.060	+0.173	−0.255	+0.014	−0.336	−0.238	+0.440	+0.407
Precipitation:										
Seeding to tillering		+.053	+.244	+.184	−.596	−.173	−.286	−.234	+.711	+.563
Tillering to heading			+.240	+.022	+.163	−.565	−.397	−.223	+.548	+.495
Heading to soft dough				+.029	−.350	+.182	−.433	−.345	+.320	+.246
Soft dough to harvest					−.017	−.025	−.226	−.625	+.136	+.048
Maximum temperatures:										
Seeding to tillering						+.079	+.286	+.253	−.441	−.259
Tillering to heading							+.218	+.083	−.403	−.534
Heading to soft dough								+.407	−.576	−.577
Soft dough to harvest									−.445	−.243
Huntley:										
Soil moisture at seeding	+.517	−.094	−.036	+.075	−.448	−.239	−.254	−.263	+.508	+.583
Precipitation:										
Seeding to tillering		−.072	+.082	+.064	−.584	−.083	−.243	−.267	+.575	+.154
Tillering to heading			+.058	+.185	+.037	−.696	−.429	−.093	+.230	+.516
Heading to soft dough				+.104	−.135	−.052	−.531	−.300	+.284	+.236
Soft dough to harvest					+.124	−.149	−.353	−.503	+.351	+.266
Maximum temperatures:										
Seeding to tillering						−.070	+.354	+.138	−.381	−.241
Tillering to heading							+.489	+.212	−.288	−.467
Heading to soft dough								+.544	−.588	−.803
Soft dough to harvest									−.596	−.484

[1] At Havre, to be significant, r must equal 0.355 at 5-percent level and 0.456 at 1-percent level; at Huntley, to be significant, r must equal 0.349 at 5-percent level and 0.449 at 1-percent level.

Soil moisture values were often taken after the crop was seeded and therefore reflect in part the precipitation within the first growth period. Compensation for such interrelationships of independent variables can be accomplished through multiple regression studies.

The standard partial regression values of table 9 can be used to indicate the independent contribution of each variable to the final grain yield. The validity of this interpretation depends upon the adequacy of sampled points in the multivariate surface. Since the study covers only 30 years, the adequacy of these data can be questioned. However, these estimates of the standard regression coefficients are the best available and are used here to evaluate factor effects.

Soil moisture supplies at seeding appear to be somewhat more important under a fallow system than under continuous cropping. This, however, may be a reflection of lack of an adequate range of soil moisture values at seeding time on the plots continuously cropped. Cole and Mathews (7) previously had pointed out that cropping sequences such as continuous cropping leave the soil exhausted of available moisture at harvest. The harvest-to-seeding fallow period under continuous cropping is not long enough to permit replenishment of soil moisture reserves. Dependence of the wheat crop under continuous cropping upon early growing-season precipitation is evidenced by the standard partial regression coefficients for the seeding-to-tillering and tillering-to-heading periods. Under both cropping systems it appears that preseasonal precipitation as reflected in soil-moisture supplies at seeding is not as important in determining wheat yields in the northern Plains as is precipitation during the growing season.

Precipitation from seeding to tillering and that from tillering to heading are both very important in determining grain yield. Precipitation from seeding to tillering is especially important in determining grain yields under a system of continuous cropping. Precipitation from heading to harvest apparently is only slightly related to the final yield of grain. Negative standard partial regression coefficients suggest that in some instances rainfall occurring after heading may actually be detrimental to the yield of wheat.

In general, high maximum temperatures tended to limit yield of wheat. After temperature effects on yield were adjusted for moisture conditions, evidence appeared that high maximum temperatures early in the growing season were beneficial to the wheat yield. This effect persisted until tillering at Havre and until heading at Huntley. Without adjustment for associated effects of precipitation, correlations between maximum temperatures and yield were negative for all phenologic periods and cropping systems at each location (table 9).

High temperatures were especially harmful after the crop had headed. Standard partial regression coefficients suggest that temperature effects were more important during this period in determining yields of wheat under fallow than under continuous cropping. Apparently moisture storage under fallow minimized the effects of precipitation on wheat yields. Consequently temperatures became more limiting under fallow than under continuous cropping.

Differences in magnitude of the standard partial regression coefficients between locations for respective growth periods and cropping systems may possibly be a reflection of differences in the soil types found at each of the locations. However, the number of

TABLE 9.—*Standard partial regression coefficients, with their respective standard errors, relating spring wheat yield to soil moisture supply at seeding and to precipitation and maximum temperatures during the growing season*

Station and cropping system	Soil moisture at seeding	Coefficient relating yield to precipitation			
		Seeding to tillering	Tillering to heading	Heading to soft dough	Soft dough to harvest
Havre:					
Continuous cropping	+0. 178 ±0. 113	+0. 437 ±0. 129	+0. 529 ±0. 129	−0. 087 ±0. 114	−0. 026 ±0. 114
Alternate cropping	+. 322 ± . 148	+. 349 ± . 154	+. 269 ± . 177	+. 159 ± . 162	−. 007 ± . 115
Huntley:					
Continuous cropping	+. 278 ± . 157	+. 354 ± . 158	+. 264 ± . 185	+. 065 ± . 150	+. 056 ± . 145
Alternate cropping	+. 306 ± . 136	−. 053 ± . 124	+. 308 ± . 142	+. 152 ± . 120	−. 059 ± . 119

Station and cropping system	Coefficient relating yield to maximum temperatures			
	Seeding to tillering	Tillering to heading	Heading to soft dough	Soft dough to harvest
Havre:				
Continuous cropping	−0. 183 ±0. 121	+0. 007 ±0. 116	−0. 119 ±0. 116	−0. 134 ±0. 125
Alternate cropping	+. 102 ± . 161	−. 269 ± . 159	−. 241 ± . 153	+. 108 ± . 172
Huntley:				
Continuous cropping	+. 041 ± . 166	+. 159 ± . 188	−. 200 ± . 212	−. 286 ± . 160
Alternate cropping	+. 059 ± . 136	+. 082 ± . 145	−. 469 ± . 176	−. 140 ± . 130

unexplained variables not directly related to soils, yet materially affecting yields, is probably so large that no major differences in any of the standard partial regression coefficients between stations can be directly attributed to soil differences.

Standard errors shown in conjunction with the standard partial regression coefficients (table 9) are in many instances far in excess of what could be termed desirable. To establish the statistical significance of these various coefficients, t values of each standard partial regression value are shown in table 10. There is a relatively large error associated with many of the calculated regression coefficients. Apparently about 30 years of crop and weather data are not sufficient to completely and satisfactorily establish climatic effects on wheat yields by the multiple regression technique. However, when all variables are considered in the regression study, the multiple correlation coefficients are all greater than 0.81 (table 11). Approximately 66 to 85 percent of the variability in wheat yields was associated with variability in the independent variables studied. When one considers that no crop data were excluded in the study for any reason, more value can be placed on the conclusions than is first apparent from examining the standard partial regression coefficients. Crop data have been included when records show that hail, insects, or other extraneous factors affected grain yields. The R values, therefore, may be somewhat conservative; but they are truly indicative of the actual variability in spring wheat yields attributable to variability in soil moisture supplies at seeding and in precipitation and maximum temperatures during crop growth.

From the standard partial regression coefficients (table 10) can be calculated the respective regression equations necessary for directly relating grain yields to the independent variables (table 12). The regression coefficients of table 12 represent the independent contribution of each variable to yield measured in pounds per 0.1 acre. Soil-moisture and precipitation coefficients indicate the pounds of grain per inch of moisture; temperature effects are measured in pounds of grain per degree of accumulated daily maximum temperatures for each growth period. For clarity of presentation and discussion of regression equations, the independent variables have been designated as follows:

X_{SM}—Soil moisture at seeding
X_{P1}—Precipitation: seeding to tillering
X_{P2}—Precipitation: tillering to heading
X_{P3}—Precipitation: heading to soft dough
X_{P4}—Precipitation: soft dough to harvest
X_{T1}—Maximum temperatures: seeding to tillering
X_{T2}—Maximum temperatures: tillering to heading
X_{T3}—Maximum temperatures: heading to soft dough
X_{T4}—Maximum temperatures: soft dough to harvest.

For comparative purposes the calculated grain yields ($\hat{Y}$) and the actual yields that were used in deriving the equations are given in table 13.

If growing-season weather could be predicted with extreme accuracy before or shortly after seeding, the equations of table 12 could be used for estimating future crop yields. Long-range weather forecasting, however, is not now sufficiently refined to permit a satisfactory advance estimate of precipitation and maximum temperatures during the growing season. Use of such a group of equations as shown in table 12 to predict wheat yield in advance of harvest would be practically worthless without extremely accurate long range weather

Table 10.—*Standard partial regression coefficients (b′) of table 9 with the associated "t" values and significance levels*

Station, cropping system, and phenologic period	Precipitation			Maximum temperatures			Soil moisture		
	b'	t	P	b'	t	P	b'	t	P
Havre:									
Continuous cropping:									
Seeding to tillering	+0. 437	3. 40	0. 01	−0. 183	−1. 51	0. 20	+0. 178	1. 58	0. 20
Tillering to heading	+. 529	4. 09	. 001	+. 007	. 58	. 60	----	----	----
Heading to soft dough	−. 087	−. 76	. 50	−. 119	−1. 03	. 40	----	----	----
Soft dough to harvest	−. 026	−. 23	. 90	+. 178	1. 07	. 30	----	----	----
Alternate cropping:									
Seeding to tillering	+. 349	2. 27	. 05	+. 102	. 63	. 60	+. 322	2. 18	. 05
Tillering to heading	+. 269	1. 52	. 20	−. 269	−1. 69	. 20	----	----	----
Heading to soft dough	+. 159	. 98	. 40	−. 241	−1. 57	. 20	----	----	----
Soft dough to harvest	−. 007	−. 005	≥. 90	+. 107	. 62	. 60	----	----	----
Huntley:									
Continuous cropping:									
Seeding to tillering	+. 354	2. 24	. 05	+. 041	. 25	. 80	+. 278	1. 77	. 10
Tillering to heading	+. 264	1. 43	. 20	+. 159	. 85	. 40	----	----	----
Heading to soft dough	+. 065	. 43	. 70	−. 199	−. 94	. 40	----	----	----
Soft dough to harvest	+. 056	. 38	. 80	−. 286	−1. 79	. 10	----	----	----
Alternate cropping:									
Seeding to tillering	−. 053	−. 43	. 70	+. 059	. 43	. 70	+. 306	2. 58	. 02
Tillering to heading	+. 308	2. 17	. 05	+. 082	. 57	. 60	----	----	----
Heading to soft dough	+. 151	1. 26	. 30	−. 469	−2. 66	. 02	----	----	----
Soft dough to harvest	−. 059	−. 50	. 70	−. 140	−1. 08	. 30	----	----	----

Table 11.—*Correlation coefficients associated with the multiple regressions of table 9*

Station and cropping system	R	R^2
Havre:		
Continuous cropping	0. 924	0. 854
Alternate cropping	. 854	. 729
Huntley:		
Continuous cropping	. 812	. 659
Alternate cropping	. 883	. 780

forecasting. The inherent lack of precision in the equation itself would be compounded with the errors associated with the unreliable advance estimates of precipitation and maximum temperatures.

At the time of seeding there is actually only one measurable environmental factor, soil moisture, that can be used as a basis for estimating crop yields.

Table 14 shows the simple correlation coefficients between soil moisture and yield, and the simple regression equations relating yield to soil moisture. It is readily apparent from the r values that soil moisture at seeding time is not highly indicative of future grain yields. In no instance was more than 34 percent of variability in grain yields associated with or explained by variability in soil moisture supplies at seeding.

As the growing season progresses, the original estimate of the expected spring wheat yields based on soil moisture only can be adjusted on the basis of actual precipitation and maximum temperatures. No long-range weather forecasting is required. Subsequent periodic improvements in yield estimates can be made until the crop is actually harvested. A series of stepwise-prediction equations of grain yields has been developed and is presented in table 15. As harvest time approaches, the yield estimate, of course, is continually improved.

The necessary regression equations (table 15) for such a stepwise prediction and the respective multiple correlation coefficients (R) (table 16) are shown for each forecasting period as the spring wheat crop continues to develop through the growing season. The regression coefficients in the equations for each phenologic period or group of periods have not been adjusted for weather in a subsequent period or group of periods.

The multiple correlation coefficients (table 16) definitely show that only a fair estimate of grain yields can be obtained early in the growing season by use of equations of table 15. Yet, based on available weather data and past records, these equations are perhaps the best means now available for mathematically estimating spring wheat yields in Montana. Through their stepwise use, fair estimates of future spring wheat yields should be available in any particular growth period of the spring wheat crop in Montana. There will always be, however, extraneous factors such as insects and hail that cannot be compensated for or included in the multiple regression equations. Furthermore, if growing-season precipitation or temperatures or combinations of these variables go far outside the range of the data used in deriving these equations, the danger of incorrect estimates will

TABLE 12.—*Partial regression coefficients associated with each of the independent variables,* X_{SM}, X_{P1}, X_{T1}, X_{P2}, X_{T2}, X_{P3}, X_{T3}, X_{P4}, *and* X_{T4}, *for predicting spring wheat yields* ($\hat{Y}$)[1]

Station and cropping system	X_{SM}	X_{P1}	X_{T1}	X_{P2}	X_{T2}	X_{P3}	X_{T3}	X_{P4}	X_{T4}	a[2]
Havre:										
Continuous cropping	6.3	11.8	−0.04	17.7	0	−4.9	−0.06	−2.3	−0.08	303.48
Alternate cropping	16.6	12.7	.03	13.1	−.14	13.2	−.17	−.9	.10	267.01
Huntley:										
Continuous cropping	9.3	12.1	.01	10.5	.08	4.4	−.10	4.8	−.28	345.77
Alternate cropping	12.0	−2.3	.02	15.7	.05	13.2	−.29	−6.5	−.18	723.69

[1] $\hat{Y}$=grain yield in pounds per 0.1 acre (total grain yield in bushels per acre$=\frac{\hat{Y}}{60}\times 10$); X_{SM}=number of inches of soil moisture at seeding; $X_{P1} \ldots X_{P4}$=number of inches of precipitation in phenological periods 1 to 4, respectively; $X_{T1} \ldots X_{T4}$=number of degrees total daily maximum temperatures for phenological periods 1 to 4, respectively.

[2] a=a constant.

TABLE 13.—*Yields calculated*[1] *by use of equations of table 12 in comparison with measured yields*

Station and year	Continuous cropping			Alternate cropping		
	Measured yield	Calculated yield	Difference between measured and calculated yields	Measured yield	Calculated yield	Difference between measured and calculated yields
Havre:	*Bu./acre*	*Bu./acre*	*Bu./acre*	*Bu./acre*	*Bu./acre*	*Bu./acre*
1917	3. 5	5. 4	−1. 9	11. 7	12. 8	−1. 1
1918	5. 7	3. 7	2. 0	5. 8	7. 6	−1. 8
1919	1. 5	1. 1	. 4	2. 2	. 6	1. 6
1920	7. 2	8. 3	−1. 1	10. 5	15. 4	−4. 9
1921	9. 7	10. 6	−. 9	19. 0	15. 8	3. 2
1922	7. 2	6. 9	. 3	12. 2	17. 6	−5. 4
1923	16. 7	17. 6	−. 9	20. 0	23. 5	−3. 5
1924	11. 8	14. 8	−3. 0	19. 0	22. 8	−3. 8
1925	16. 3	15. 6	. 7	18. 5	21. 6	−3. 1
1926	4. 3	2. 3	2. 0	13. 5	17. 3	−3. 8
1927	26. 2	24. 8	1. 4	37. 7	38. 1	−. 4
1928	16. 0	12. 5	3. 5	41. 3	28. 5	12. 8
1929	8. 4	10. 0	−1. 6	15. 7	16. 4	−. 7
1930	2. 2	4. 1	−1. 9	11. 3	11. 9	−. 6
1931	. 8	. 4	. 4	3. 0	3. 8	−. 8
1932	21. 7	16. 3	5. 4	27. 2	22. 5	4. 7
1933	. 8	3. 9	−3. 1	12. 8	14. 0	−1. 2
1934[2]	. 2	4. 1	−3. 9	. 5	12. 5	−12. 0
1935	4. 2	3. 8	. 4	13. 2	13. 0	. 2
1936	0	0	0	. 3	0	. 3
1937	1. 2	4. 9	−3. 7	5. 5	8. 4	−2. 9
1938	13. 2	14. 4	−1. 2	22. 7	22. 7	0
1939	1. 7	7. 6	−5. 9	9. 8	21. 3	−11. 5
1940	6. 2	7. 8	−1. 6	10. 8	8. 7	2. 1
1941	4. 0	1. 9	2. 1	19. 3	13. 5	5. 8
1942	19. 2	15. 4	3. 8	24. 2	24. 9	−. 7
1943	16. 0	15. 2	. 8	31. 3	28. 8	2. 5
1944	6. 3	7. 5	−1. 2	31. 2	19. 7	11. 5
1945	2. 8	3. 9	−1. 1	9. 0	6. 7	2. 3
1946	3. 0	. 3	2. 7	16. 7	9. 3	7. 4
1947	5. 2	0	5. 2	13. 7	10. 7	3. 0
Huntley:						
1913	16. 0	13. 8	2. 2	22. 7	26. 9	−4. 2
1914	18. 3	8. 0	10. 3	19. 5	22. 3	−2. 8
1915	24. 5	23. 2	1. 3	36. 5	40. 6	−4. 1
1916	5. 8	6. 3	−. 5	13. 5	11. 8	1. 7
1917	7. 8	10. 4	−2. 6	11. 3	13. 5	−2. 2
1918	1. 5	11. 6	−10. 1	18. 8	22. 9	−4. 1
1919	0	0	0	. 7	0	. 7
1920	8. 2	14. 6	−6. 4	6. 8	23. 7	−16. 9
1921	3. 0	6. 6	−3. 6	17. 7	18. 1	−. 4
1922	20. 7	17. 6	3. 1	19. 3	23. 7	−4. 4
1923	6. 3	11. 7	−5. 4	10. 3	15. 5	−5. 2
1924	26. 7	17. 4	9. 3	21. 8	23. 5	−1. 7
1925	7. 0	6. 3	. 7	10. 0	15. 1	−5. 1
1926	0	4. 7	−4. 7	1. 5	11. 8	−10. 3
1927	24. 2	21. 6	2. 6	20. 3	17. 4	2. 9
1928	3. 8	6. 8	−3. 0	20. 5	24. 7	−4. 2
1929	2. 8	. 7	2. 1	9. 7	9. 7	0
1930	0	4. 0	−4. 0	0	9. 9	−9. 9
1931[3]	0	3. 2	−3. 2	0	. 2	−. 2
1932	2. 3	7. 8	−5. 5	2. 7	7. 9	−5. 2
1933	0	4. 1	−4. 1	. 5	. 8	−. 3

TABLE 13.—*Yields calculated*[1] *by use of equations of table 12 in comparison with measured yields*—Continued

Station and year	Continuous cropping			Alternate cropping		
	Measured yield	Calculated yield	Difference between measured and calculated yields	Measured yield	Calculated yield	Difference between measured and calculated yields
	Bu./acre	*Bu./acre*	*Bu./acre*	*Bu./acre*	*Bu./acre*	*Bu./acre*
1934	0	0	0	4. 5	4. 9	—. 4
1935	1	5. 8	—4. 8	2. 5	9. 0	—6. 5
1936[3]	0	5. 5	—5. 5	. 2	0	. 2
1937	2. 0	1. 7	. 3	5. 5	5. 3	. 2
1938	30. 3	15. 8	14. 5	28. 8	20. 8	8. 0
1939	7. 5	11. 1	—3. 6	12. 3	23. 4	—11. 1
1940	4. 3	4. 8	—. 5	10. 8	14. 2	—3. 4
1941	5. 0	9. 2	—4. 2	2. 5	12. 8	—10. 3
1942	23. 5	23. 3	. 2	23. 3	17. 5	5. 8
1943	9. 0	6. 0	3. 0	31. 7	24. 1	7. 6
1944	9. 0	13. 9	—4. 9	47. 5	40. 5	7. 0
1945	5. 8	2. 4	3. 4	20. 3	21. 5	—1. 2
1946	5. 5	3. 2	2. 3	18. 3	16. 2	2. 1

[1] Calculated yields were recorded as 0 when $\hat{Y}$ was either 0 or less than 0.
[2] Yields of this year were affected by hail damage to the crop.
[3] Yields of this year were affected by insect damage to the crop.

increase. Additional limitations of multiple regression equations for use as a forecasting formula have been fully discussed by Sanderson (*15*).

Use of the multiple regression equations for forecasting purposes definitely requires caution and good judgment. As new crop and weather data become available, the calculated regression coefficients of tables 12 and 15 should be recomputed continually to improve the accuracy of the derived estimates.

TABLE 14.—*Regression equations relating spring wheat yield to soil moisture supply at seeding without adjustment for growing-season weather*

Station and cropping system	Equation [1]	r
Havre:		
Continuous cropping	$\hat{Y}=-50.72+15.487X$	+0. 440
Alternate cropping	$\hat{Y}=-93.394+20.988X$	+. 407
Huntley:		
Continuous cropping	$\hat{Y}=-82.051+16.932X$	+. 508
Alternate cropping	$\hat{Y}=-120.085+22.823X$	+. 583

[1] $\hat{Y}$=grain yield in pounds per 0.1 acre; X=total soil moisture in inches.

TABLE 15.—*Regression equations for stepwise prediction of spring wheat yield from seeding through successive phenologic periods*

Prediction basis, station, and cropping system	Equation [1]
Soil moisture at seeding plus precipitation and maximum temperatures from seeding to tillering:	
Havre:	
Continuous	$\hat{Y}=5.98+3.31X_{SM}+17.223X_{P1}-0.0075X_{T1}$
Alternate	$\hat{Y}=-240.92+12.33X_{SM}+22.142X_{P1}+0.0521X_{T1}$
Huntley:	
Continuous	$\hat{Y}=-57.26+9.54X_{SM}+14.487X_{P1}-0.0013X_{T1}$
Alternate	$\hat{Y}=-104.90+23.65X_{SM}-3.279X_{P1}-0.0043X_{T1}$
Soil moisture at seeding plus precipitation and maximum temperatures from seeding to tillering and from tillering to heading:	
Havre:	
Continuous	$\hat{Y}=-354.87+6.56X_{SM}+2.019X_{P1}+15.955X_{P2}+0.1032X_{T1}-0.0075X_{T2}$
Alternate	$\hat{Y}=244.21-8.96X_{SM}+14.507X_{P1}+21.459X_{P2}-0.0001X_{T1}-0.0953X_{T2}$
Huntley:	
Continuous	$\hat{Y}=-149.48+10.99X_{SM}+14.911X_{P1}+13.169X_{P2}+0.0012X_{T1}+0.0284X_{T2}$
Alternate	$\hat{Y}=-39.62+19.49X_{SM}-1.284X_{P1}+20.785X_{P2}-0.0146X_{T1}-0.0265X_{T2}$
Soil moisture at seeding plus precipitation and maximum temperatures from seeding to tillering, from tillering to heading, and from heading to soft dough:	
Havre:	
Continuous	$\hat{Y}=235.32+6.99X_{SM}+11.621X_{P1}+18.405X_{P2}-3.471X_{P3}-0.0436X_{T1}+0.0017X_{T2}-0.0668X_{T3}$
Alternate	$\hat{Y}=356.60+15.53X_{SM}+13.692X_{P1}+12.248X_{P2}+11.215X_{P3}+0.0340X_{T1}-0.1364X_{T2}-0.1569X_{T3}$
Huntley:	
Continuous	$\hat{Y}=144.66+10.37X_{SM}+14.323X_{P1}+8.845X_{P2}+3.701X_{P3}+0.0330X_{T1}+0.0845X_{T2}-0.1985X_{T3}$
Alternate	$\hat{Y}=567.14+12.23X_{SM}+1.429X_{P1}+14.152X_{P2}+11.910X_{P3}+0.0213X_{T1}+0.0440X_{T2}-0.3216X_{T3}$

Soil moisture at seeding plus precipitation and maximum temperatures from seeding to tillering, from tillering to heading, from heading to soft dough, and from soft dough to harvest:	
Havre:	
Continuous	$\hat{Y}=303.48+6.26X_{SM}+11.762X_{P1}+17.662X_{P2}+4.944X_{P3}-2.331X_{P4}-0.0391X_{T1}+0.0023X_{T2}-0.0586X_{T3}-0.0793X_{T4}$
Alternate	$\hat{Y}=267.01+16.63X_{SM}+13.671X_{P1}+13.073X_{P2}+13.178X_{P3}-0.9344X_{P4}+0.0317X_{T1}-0.1352X_{T2}-0.1723X_{T3}+0.0993X_{T4}$
Huntley:	
Continuous	$\hat{Y}=345.77+9.28X_{SM}+12.078X_{P1}+10.466X_{P2}+4.422X_{P3}+4.795X_{P4}+0.0099X_{T1}+0.0778X_{T2}-0.0956X_{T3}-0.2827X_{T4}$
Alternate	$\hat{Y}=723.69+11.99X_{SM}-2.317X_{P1}+15.670X_{P2}+13.186X_{P3}-6.509X_{P4}+0.0182X_{T1}+0.0515X_{T2}-0.2881X_{T3}-0.1772X_{T4}$

[1] Symbols have the same meanings as in table 12.

TABLE 16.—*Correlation coefficients for regression equations (of table 15) used in stepwise prediction of spring wheat yield*

Station and cropping system	X variables used in calculations	R or r	R^2 or r^2
Havre:			
Continuous	SM	+0.440	0.194
	SM, (P_1, T_1)	.716	.513
	SM, (P_1, T_1), (P_2, T_2)	.863	.745
	SM, (P_1, T_1), (P_2, T_2), (P_3, T_3)	.918	.843
	Variables for complete growing season	.924	.854
Alternate	SM	+.407	.166
	SM, (P_1, T_1)	.610	.372
	SM, (P_1, T_1), (P_2, T_2)	.815	.664
	SM, (P_1, T_1), (P_2, T_2), (P_3, T_3)	.848	.719
	Variables for complete growing season	.854	.729
Huntley:			
Continuous	SM	+.508	.258
	SM, (P_1, T_1)	.626	.392
	SM, (P_1, T_1), (P_2, T_2)	.690	.476
	SM, (P_1, T_1), (P_2, T_2), (P_3, T_3)	.780	.608
	Variables for complete growing season	.812	.659
Alternate	SM	+.583	.340
	SM, (P_1, T_1)	.586	.343
	SM, (P_1, T_1), (P_2, T_2)	.726	.527
	SM, (P_1, T_1), (P_2, T_2), (P_3, T_3)	.871	.759
	Variables for complete growing season	.883	.780

Summary

Through the use of simple correlation and multiple regression techniques, the relation of soil moisture supply at seeding and those of precipitation and total daily maximum temperatures within the growing season to yield of spring wheat were studied in the Plains area of Montana. The study was based on data for spring wheat grown continuously and also alternated with fallow at each of two stations, North Montana (Havre) and Huntley. Data for the two stations, respectively, covered periods of 31 and 34 years.

Cumulative frequencies of yield levels were calculated for continuous cropping and for cropping alternated with fallowing at each station.

Grain yield at both Havre and Huntley was significantly correlated with soil moisture supply at seeding. Cropping system had little effect on the degree of correlation. Precipitation between seeding and heading appeared to be more critical in relation to yield than precipitation in the remainder of the growing season. Correlation with yield was higher for temperatures after heading than for precipitation after heading. Multiple regression analyses indicated that about 66 to 85 percent of the variation in spring wheat yield was associated with variation in the independent variables studied.

A method was developed for estimating the prospective spring wheat yield at seeding and progressively improving the estimate as the growing season advances.

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U.S. GOVERNMENT PRINTING OFFICE: 1960